

# NASA Strategic Roadmap: Origin, Evolution, Structure, and Destiny of the Universe

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## ABSTRACT

The NASA strategic roadmap on the Origin, Evolution, Structure and Destiny of the Universe is one of 13 roadmaps that outline NASA's approach to implement the vision for space exploration. The roadmap outlines a program to address the questions: What powered the Big Bang? What happens close to a Black Hole? What is Dark Energy? How did the infant universe grow into the galaxies, stars and planets, and set the stage for life? The roadmap builds upon the currently operating and successful missions such as HST, Chandra and Spitzer. The program contains two elements, Beyond Einstein and Pathways to Life, performed in three phases (2005-2015, 2015-2025 and >2025) with priorities set by inputs received from reviews undertaken by the National Academy of Sciences and technology readiness. The program includes the following missions: 2005-2015 GLAST, JWST and LISA; 2015-2025 Constellation-X and a series of Einstein Probes; and >2025 a number of ambitious vision missions which will be prioritized by results from the previous two phases.

**Keywords:** telescopes, optics, interferometry, astrophysics, roadmap.

## 1. INTRODUCTION

In January 2004 President George W. Bush announced that the U.S. space program would undertake "a renewed period of discovery". NASA was charged with focusing its efforts on exploration and includes human and robotic missions to the Moon, Mars, and beyond. A Presidential Commission on the Implementation of this Space Exploration Policy issued a report in June 2004 and endorsed the overall plan, and gave more details on the science goals. In late 2004 NASA Administrator Sean O'Keefe announced a new strategic planning process in which NASA would develop a set of roadmaps for each of the major exploration objectives. This paper summarizes the results of the strategic roadmap of universe exploration to understand its origin, structure, evolution and destiny.

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## 2. OVERVIEW

Science is now poised to answer some of humanity's deepest questions, such as how the universe came into being; how it formed the galaxies, stars, and planets that set the stage for life; and whether there is life on other worlds. The scientific pursuit of our origin, structure, evolution and destiny requires deep and detailed explorations into space and time, and challenges the limits of America's technical capabilities in space. This roadmap articulates a long-term plan for scientific exploration of the universe, from the Big Bang to life. It is composed of two program elements, the Beyond Einstein Program and the Pathways to Life Program.

The **Beyond Einstein Program** explores the ultimate extremes of nature: the birth of the universe, the edges of space and time near black holes, and the darkest and emptiest space between the galaxies. It will determine the initial conditions and natural laws that govern everything that happens in the universe, from beginning to end. This program takes up the challenge to explore the origin and destiny of the universe through three roadmap objectives:

Find out what powered the Big Bang.

Observe how black holes manipulate space, time and matter.

Uncover the nature of the mysterious dark energy pulling the universe apart.

The Beyond Einstein program's cornerstone missions are the Laser Interferometer Space Antenna (LISA), the first instrument in space to measure spacetime ripples called gravitational waves, and Constellation-X (Con-X), a path-breaking X-ray telescope that can study matter near black holes. A focused line of more specialized Einstein Probe missions is dedicated to specific studies of black hole discovery, the cosmic inflation that powered the Big Bang, and the dark energy propelling the cosmic expansion today. Forward-looking technology development, as well as foundational and exploratory studies in theory, modeling, and predictive simulation, aim ultimately toward two Vision missions: the Big Bang Observer, an ultra-sensitive gravitational wave observatory, and the Black Hole Imager, an X-ray interferometer.

The simple Big Bang ultimately created a rich structure, giving rise to galaxies, stars and planets. Peering back nearly 14 billion years, this global history — from epoch to epoch, from the formless infant universe through nascent galaxy building to the formation of solar systems — can be traced by direct observations of distant space. For example, all-sky images from the Wilkinson Microwave Anisotropy Probe (WMAP) reveal the afterglow of the Big Bang, a remnant primordial radiation created by faint vibrations in matter and light half a million years after the Big Bang, triggered by the event itself. The more advanced ESA-NASA Planck Surveyor mission and eventually the Beyond Einstein Inflation Probe will measure these vibrations in exquisite detail. The weak ripples in gas and dark matter — a little more matter here, a little less there — later created the first stars, then the quasars powered by supermassive black holes, and finally the great cosmic web of galaxies linked by invisible rivers of dark matter and hot, tenuous gas. Con-X and LISA explore the era when massive black holes dominated; other Beyond Einstein missions will probe the era when dark energy became the dominant force in the universe.

As the universe evolved to the present day, stars played increasingly dominant roles in the evolution of matter and complex structure. Stars are the sources of the energy, light, and chemical elements that drive the cosmic cycling of matter into new generations of stars, planets, and eventually life. From hydrogen and helium created in the Big Bang comes carbon, oxygen, nitrogen and life itself. The **Pathways to Life Program** explores the formation and evolution of all of this grand system. It takes up the challenge to explore the structure and evolution of the universe through one overarching objective:

Determine how the infant universe grew into the galaxies, stars and planets, setting the stage for life.

This objective has three key components:

Map directly the structure and evolution of the Cosmic Web.

Map the flows of energy and matter between whole systems and their constituent parts, from galaxies to stars and planets.

Trace the evolution of nuclei, atoms, and molecules that became life.

The Pathways to Life program builds on the historic legacy of the Hubble Space Telescope, and includes the airborne Stratospheric Observatory For Infrared Astronomy (SOFIA), the James Webb Space Telescope (JWST), the Gamma-ray Large-Area Space Telescope (GLAST), competed Probes, and the Pathways to Life Observatories. Con-X, LISA, and the Einstein Probes will contribute significantly. The Pathways to Life Observatories encompass several possible approaches:

A Far Infrared/ Submillimeter Interferometer (FIRSI), of which SPECS is an example

A Large UV/Optical Telescope (LUVO)

A UV/Optical Interferometer (UVOI), of which Stellar Imager is an example

A large area, high spatial resolution X-Ray Observatory generically titled "Early Universe X-ray Observer" (EUXO), of which Gen-X is an example

An advanced Compton gamma-ray telescope generically titled "Nuclear Astrophysics Compton Telescope" (NACT), of which ACT is an example

The Single Aperture Far-Infrared Telescope (SAFIR)

It is too soon to select the order or priority of these approaches. This will be left to future National Academy of Sciences studies, and based on the results from the currently planned missions such as JWST and Con-X.

All of these explorations require the development of complex space missions with unprecedented capabilities, from new ultra-sensitive detectors and precision optics, to multiple spacecraft flying in formation to subatomic accuracy. New technology development is systematically incorporated into the multiple stages of the Beyond Einstein and Pathways to Life programs. The overall plan maximizes investment return by focusing on strategic technologies, where each development pays off multiple times.

Beyond the strategic space missions, NASA's scientific success depends on rapid and flexible response to new discoveries, inventing new ideas and theoretical tools supporting space science initiatives, converting hard-won data into scientific understanding, and developing promising technologies that are later incorporated into major missions. These activities are supported through a balanced portfolio of competed Research and Analysis (R&A), Probe, Discovery, Explorer, and sub-orbital programs, which collectively are designed to guarantee the continued vitality of NASA's overall space science vision, reduce major mission risks, and optimize the return on NASA's capital, technology, and manpower investments. Importantly, NASA, through its Education and Public Outreach programs and through the R&A program's support of student and postdoctoral researchers at America's universities, plays a critical role in educating the nation and training the next generation of explorers.

### 3. MISSION PRIORITIES

The highest priority missions are the Beyond Einstein Great Observatories LISA and Constellation-X. These were both highly ranked by the National Academy of Sciences Decadal Survey and their science has also been highly ranked in several other reports. The science questions these missions address will provide crucial information necessary to make key decisions by the middle of phase 2, in order to prioritize and begin the Visions Missions at the start of phase 3. The next priority is the competed line of Probes to address focused science questions, central to the Beyond Einstein program. These competed missions will begin with the Joint Dark Energy Mission, and then continue at 3 to 4 yr intervals with the Black Hole Finder Probe and the Inflation Probe (with the mission order determined by technology readiness).

#### Mission Summary for Universe Exploration

Strategic Observatories providing breakthrough capabilities

GLAST (Phase 1): Jets from black holes and dark matter decay signatures  
 Pathways to Life: JWST (Phase 1): First galaxies and stars  
 Beyond Einstein: LISA (Phase 1): Gravitational waves from many sources, how space and time behave around black holes and constrain dark energy  
 Beyond Einstein: Constellation-X (Phase 2): Observe matter falling into black holes & address the mysteries of dark matter and dark energy

Completed Missions that address focused science questions through scientist-led investigations with a range of sizes, up to a strict cost cap of \$600M

Explorers: Missions linked to Universe Exploration strategic goals (all phases)

Einstein Probe: Joint Dark Energy Mission (JDEM) (first prioritized probe) (Phase 2)

Einstein Probe: Black Hole Finder Probe (BHFP) (Phase 2)

Einstein Probe: Inflation Probe (IP) (Phase 2)

Pathways to Life (Probe): What is the nature of the Cosmic Web?

Vision Missions that result from long term objectives (late Phase 2, Phase 3)

Beyond Einstein: Big Bang Observer (BBO)

Beyond Einstein: Black Hole Imager (BHI)

Pathways to Life Observatories

## Universe Exploration Timeline

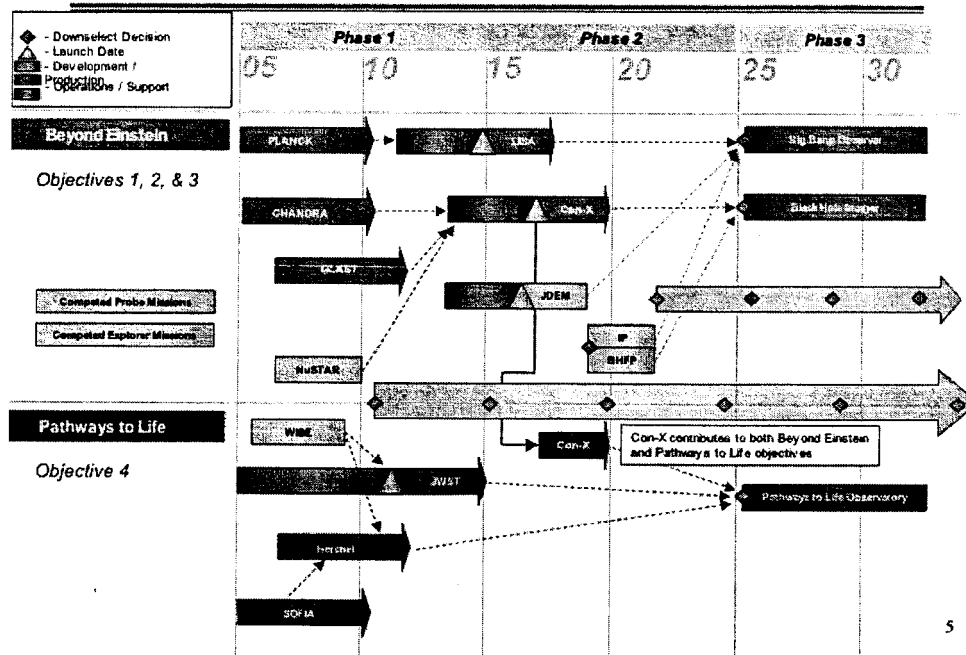


Figure 1 Roadmap timeline for Universe Exploration.